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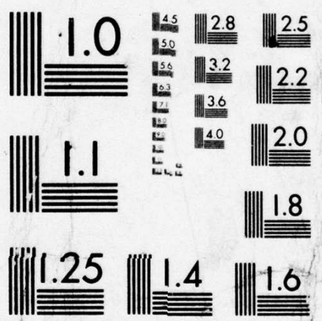

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RESPONSE OF MATERIALS TO IMPULSIVE LOADING

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 COLLEGE PARK AVENUE
DAYTON, OHIO 45469

MARCH 1976

TECHNICAL REPORT AFML-TR-76-17
FINAL REPORT FOR PERIOD DECEMBER 1972 - NOVEMBER 1975

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This report describes work conducted on the response of composite materials to foreign object damage.
The damage inflicted to both metal matrix and resin matrix composites was investigated by measuring the post impact residual mechanical properties of selected materials. Specimens were mounted as simply supported cantilevered beams and impacted with steel or rubber spheres. The residual tensile and fatigue strength of the material was then determined. The impact resistance of the composites investigated was shown to be much lower than that for → next page

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20. ABSTRACT (continued)

titanium. The important mechanisms of material damage were identified and described in terms of a fracture mechanics based model.

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SECTION I

INTRODUCTION

This report summarizes and reviews a series of foreign object impact investigations conducted under Contract F33615-73-C-5027. These studies were primarily directed to understanding the processes of local impact damage in composite materials subjected to hard and soft body impacts. A limited series of tests to investigate the structural response of cantilever beams and the impact resistance of ceramics was also undertaken.

Jet engines ingest a variety of objects in normal operation. These objects vary from small pebbles, bolts, rivets and dust, through hand tools and other maintenance items inadvertently left in the engine, to large sections of tire treads, ice balls and birds. The damage inflicted to fan blades by the impact of these objects ranges from minor blade dents, which pose maintenance problems, to massive local and structural blade damage which can threaten engine operation and integrity.

Current jet engine fan blades are fabricated with titanium and steel alloys and have proved to be reasonably resistant to foreign object damage (FOD). For many reasons, high strength composites are attractive fan blade materials and considerable effort has been expended to develop composite fan blades. However, the FOD resistance of composites has not been adequate to permit incorporation of composite fan blades in current engine designs.

This report reviews a series of investigations in which the response of composite materials to FOD was examined. The studies primarily centered on the investigation and characterization of local damage effects, that is the response of the material in the immediate vicinity of the impact. A short investigation was addressed to structural damage effects. An investigation of the impact resistance of high temperature ceramics which are candidate turbine materials was also undertaken.

In addition to the investigations reported herein other activities were conducted under this contract. These activities and the reports describing them are listed below;

1. Hypervelocity rain erosion.

   "Water Drop/Bow Shock Interactions", Barber, J. P., Grood, E. S., Taylor, H. R. and Hopkins, A. K., AFML-TR-75-105.

"High Speed Laser Photographic Techniques for Hypervelocity Erosion Studies", Barber, J. P. and Taylor, H. R., presented at the 6th Congress on Instrumentation in Aerospace Simulation Facilities, Ottawa, 1975.

2. Bird impact loading.

"Characterization of Bird Impacts on a Rigid Plate: Part I", Barber, J. P., Taylor, H. R. and Wilbeck, J. S., AFFDL-TR-75-5.

"Bird Impact Forces in Aircraft Windshield Design", Peterson, R. L. and Barber, J. P., AFFDL-TR-75-150 also presented at The Conference on Aerospace Transparent Materials and Enclosures, Atlanta, November 1975.

SECTION II

EXPERIMENTS

The work described in this report was devoted to investigating the response of jet engine fan and turbine blade materials to the impact of various objects representative of those likely to be encountered during actual engine operation. Steel BB's were used to simulate the damage due to objects such as rivets, bolts, hard tools and stones, and RTV-11 rubber spheres were used to simulate the damage due to birds, tire treads and other soft bodies. The studies reported in the following paragraphs were directed to measuring and understanding the damage inflicted on advanced composite materials by these threats. The impact testing was conducted in the Air Force Materials Laboratory, Impact Mechanics Laboratory. The analyses of the experimental results were conducted by various organizations and individuals as acknowledged in the text.

2.1 RESIDUAL PROPERTIES OF COMPOSITE MATERIALS

An extensive series of tests were undertaken to assess the damage inflicted to composite materials by various types of ballistic impact. The damage was assessed in terms of residual, or post impact, properties of the material. In brief, a certain mechanical property of the candidate material was selected and measured. A series of samples of the material were then impacted in a controlled manner. The selected mechanical property was then remeasured on the impact damaged specimens and the degradation of the measured property determined. A number of properties were investigated and the results are outlined in the following sections.

2.1.1 Bending Fatigue Strength

Instabilities in the air flow through a jet engine fan induce flutter. This flutter produces low amplitude blade bending and can result in bending fatigue failure of the blade. The bending fatigue strength of blade materials and its degradation by impact damage are therefore important design parameters.

The material selected for these experiments was a unidirectional boron/aluminum composite consisting of 50% by volume of 0.14 mm diameter boron fibers imbedded in a 6061 aluminum matrix. A series of control experiments

were conducted on Ti-6-4, a titanium alloy typical of current fan blade materials.

The B/Al-6061 was cut into standardized samples and the bending fatigue strength in the undamaged condition determined experimentally with a four point bending test. "Undamaged" S-N (Stress vs. cycles to failure) curves were obtained up to 10^7 cycles.

Another set of samples were then mounted against wooden back-up blocks and impacted in the center with steel BB's at velocities of 46, 69, 92 and 138 m/s. The lower limit was the minimum velocity which produced measurable damage.

The impact damaged samples were then mounted in the bending fatigue test machine and cycled to failure. S-N curves were generated at each of the four impact velocities and the degradation of bending fatigue strength evaluated. The results are shown in Figure 1 taken from Gray[1]. The results and conclusions were reported in greater detail by Gray[1] and were summarized as follows.

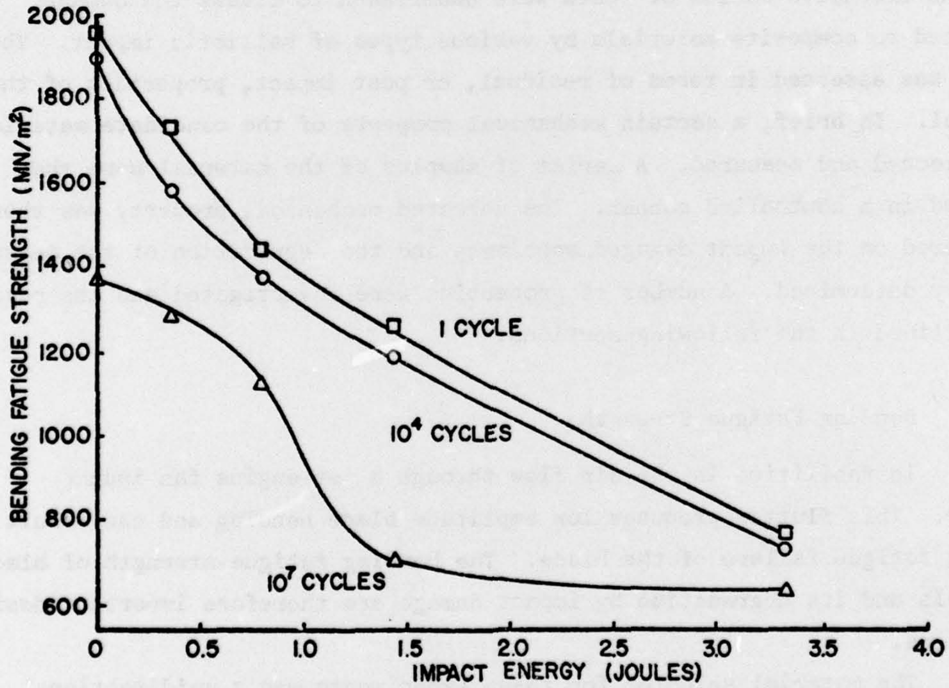

Figure 1. Residual Fatigue Strength Versus Impact Energy, B/Al-6061 (From Gray[1])

Unidirectional B/Al-6061 incurs more physical damage than does Ti-6-4 for a given impact energy. An optical measurement of an impact-induced crack, visible on the surface of the B/Al-6061 composite, may be considered as the size of a through-the-thickness crack. This was demonstrated for small cracks (1.42 mm) and thin materials (0.97 mm) but could possibly apply to other situations as long as the crack length to material thickness ratio is the same as above (approximately 1.5). Foreign object damage degrades the fatigue characteristics of Ti-6-4 less severely than it does the fatigue characteristics of B/Al-6061. The static bending strength of unidirectional B/Al-6061 appears to be crack sensitive. That is, static strength is affected by crack-induced stress concentrations. For long fatigue lives (10^7 cycles), unidirectional B/Al-6061 is insensitive to cracks. High cycle fatigue strength may be computed on the basis of uncracked cross-sectional area. The normal stress equation, $\sigma = P/A$, and the beam equation, $\sigma = Mc/I$, do not give valid results if a measurement of true constituent stress in a composite is required. However, if a characterization of the load-bearing capacity of a composite is desired, then these equations may be used as long as comparisons made on either type of test are keyed to a control experiment.

2.1.2 Tensile Fatigue and Tensile Strength

Jet engine fan blades experience considerable axial tension in operation due to the centrifugal forces on the blade. These forces are high, requiring high tensile strength materials to withstand them. The forces also cycle during start up and shut down resulting in tensile fatigue of the blade materials. It is therefore important to evaluate the effect of impact damage on the residual tensile and tensile fatigue strength of blade materials in order to assess the possible service degradation due to FOD. The effects of both hard and soft body impacts were investigated and an analytical study of the process was initiated.

2.1.2.1 Soft Body Impacts

The material selected for this investigation was a B/Al-6061 unidirectional composite composed of 50% by volume of 0.14 mm diameter boron fibers in a matrix of 6061 aluminum. Ti-6-4 was used as a control material.

The tensile and tensile fatigue strength of undamaged specimens of the material were determined. Specimens were mounted in a target assembly

capable of applying tensile prestress to the samples. The samples were impacted in the center with 4.50 mm diameter RTV spheres at various velocities and five levels of load controlled tensile prestress; 0, 152 MN/m^2, 303 MN/m^2, 461 MN/m^2, and 620 MN/m^2.

The results of the residual tensile strength tests on B/Al are displayed in Figure 2. The residual strength was normalized to the undamaged strength. There is no detectable degradation of the residual strength by impacts below 460 m/s. At velocities just above 460 m/s the residual strength falls rapidly. The residual strength in this region declines with increasing prestress. That is, in a range of impact velocities above 460 m/s, prestress appears to increase the effective damage. The specimens broke at impact for velocities in the region of 600 to 760 m/s. At higher velocities (above 900 m/s) the residual strength becomes relatively independent of impact velocity and prestress. In this region the residual strength was identical to that of a specimen with a drilled hole the same diameter as the projectile.

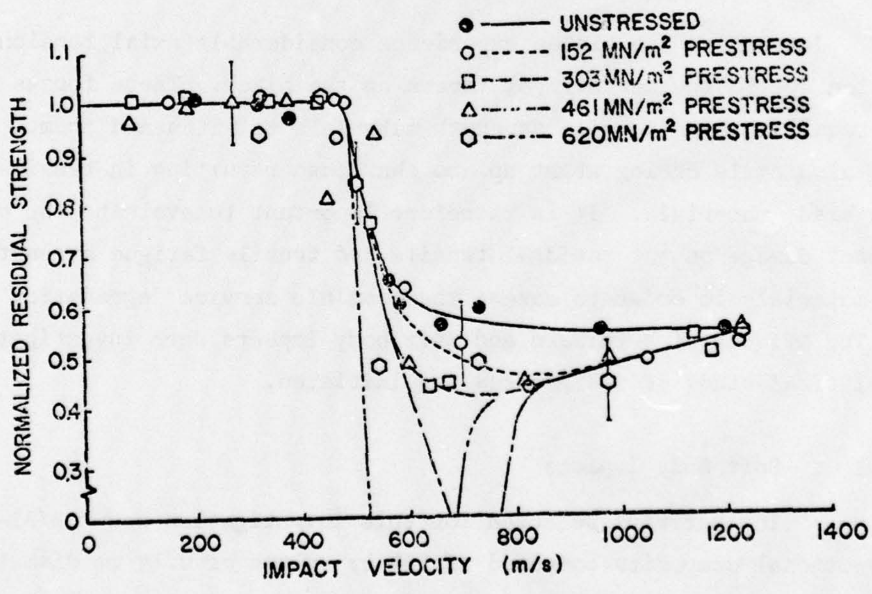

Figure 2. Normalized Residual Strength Versus Impact Velocity for B-6061 Al, Impacted with RTV Spheres. (From Jacques[2]).

It proved to be very difficult to measure the fatigue strength of this composite as the material either failed on the first cycle or ran to 10^7 cycles without failure. It was therefore decided to investigate the effects of cyclic loading on the residual tensile strength. The samples were impacted, fatigued and then tensile tested. During the fatiguing process longitudinal cracks propagated from the impact site towards the doublers. Fatigue loading was stopped and the residual tensile strength measured when the cracks reached the doublers. The results are shown for two levels of impact prestress in Figures 3 and 4. The fatigue process appeared to significantly *increase* the residual strength. Axial fatigue apparently blunts the transverse cracks in uniaxial B/Al-6061 and increases the growth of longitudinal cracks. Failures in post impact fatigued samples propagated from the ends of the longitudinal cracks rather than from the impact site.

A fracture analysis of the specimen failures was conducted. The width of the impact flaw (hole and/or crack) was measured and the failure stress calculated. The results are presented in Figure 5.

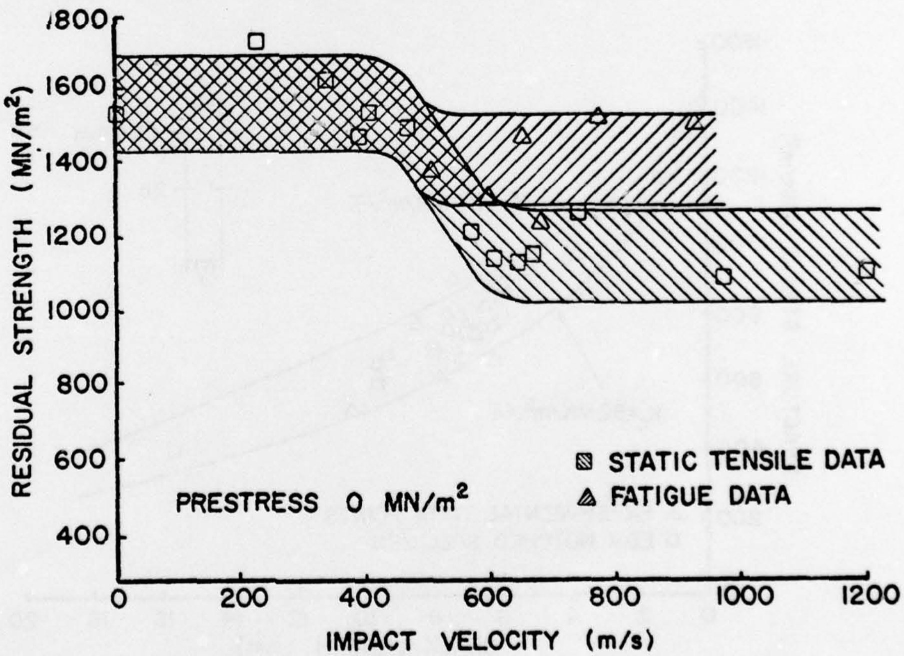

Figure 3. Residual Strength of B-6061 Al Versus Impact Velocity Based on Uncracked Area, Tensile and Fatigue Data, Unstressed, Thickness 1.35 mm. (From Jacques[2]).

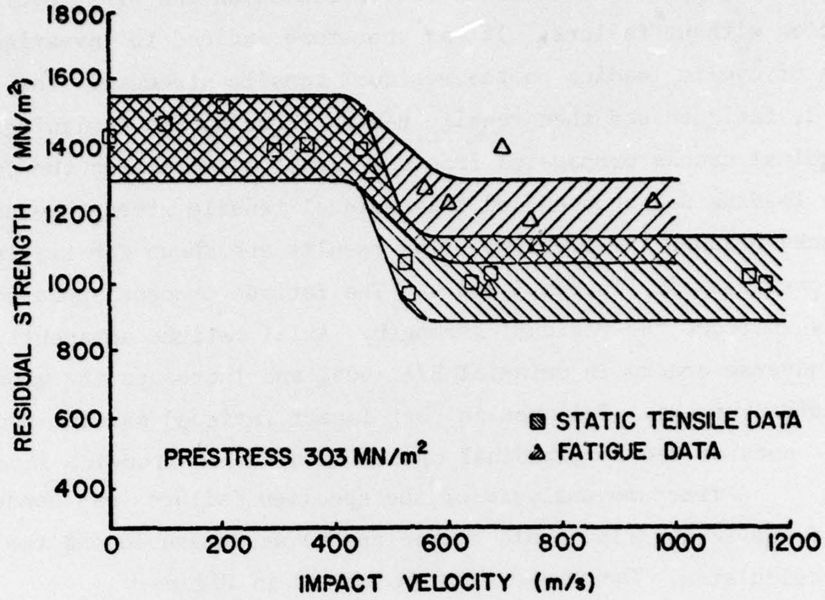

Figure 4. Residual Strength of B-6061 Al Versus Impact Velocity Based on Uncracked Area, Tensile and Fatigue Data, Prestress 303 MN/m^2 Thickness 1.35 mm. (From Jacques[2])

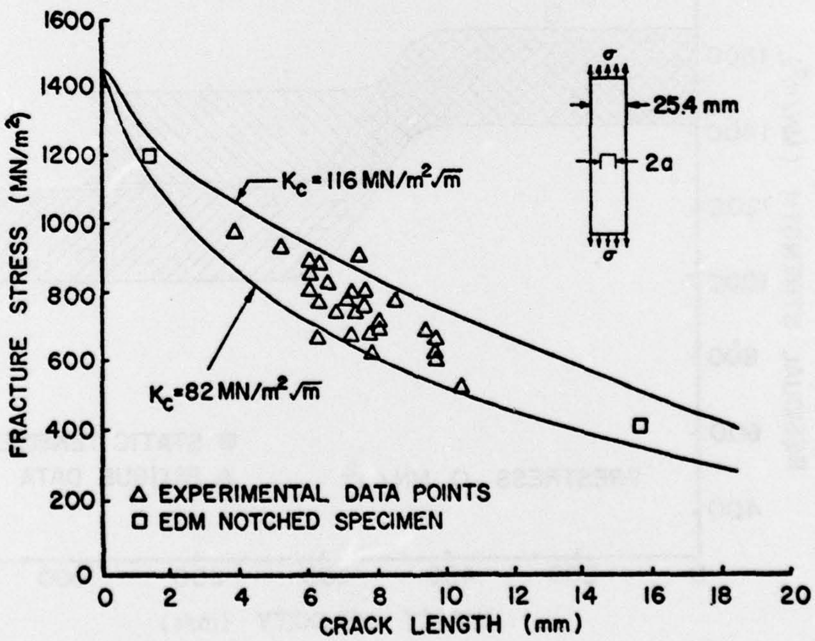

Figure 5. Comparison of Experimental and Theoretical Fracture Toughness (From Jacques[2]).

The theoretical value for a center cracked panel is the upper bound [$k_c = 116\ MN/m^2\ \sqrt{m}$] while a lower bound of $k_c = 82\ MN/m^2\ \sqrt{m}$ appears to span the scatter in the data.

The experiment and results are reported in greater detail by Jaques[2]. The conclusions he found are summarized in the following paragraph.

Unidirectional B/Al-6061 suffers a much higher degree of physical damage than Ti-6-4 for a given impact velocity. The measurement of cracks from X-radiographs was an unsatisfactory procedure for obtaining accurate through-the-thickness crack lengths. Transverse cracks measured from radiographs were always smaller than the identical cracks measured directly from the specimen. At a given velocity, impact damage increased and residual tensile strength decreased with increasing specimen prestress. The composite lost over 50% of its ultimate tensile strength for impact velocities between 460 m/s and 610 m/s for all prestress levels. The composite lost no additional strength after a clean plug was produced. Unidirectional B/Al-6061 was comparatively notch-insensitive in axial fatigue due to the crack blunting effect caused by matrix shear cracking at low stresses. A uniformly-loaded, center-cracked, finite-width, fracture mechanics model could be used to predict fracture stress for impacted unidirectional B/Al-6061 provided the concentration of longitudinal tensile stress reaches a maximum at the crack tip before longitudinal matrix shear cracks occur.

The differences in the x-radiographically and directly measured crack lengths was difficult to understand and may have been simply due to the difficulties of crack detection in the x-radiographs.

2.1.2.2 Hard Body Impacts

This study was separated into two basic areas of interest: the residual static tensile strength and the residual tensile strength after fatigue. A B/Al-6061 unidirectional composite composed of 50% by volume of 0.14 mm diameter boron fibers in a 6061 aluminum matrix was used. Foreign object damage was inflicted to thin, flat, rectangular specimens by impact with a steel spherical projectile (4.50 mm diameter). Various levels of tensile prestress were applied during impact. The prestress was varied from 0 to 620 MN/m^2, in order to simulate the stresses found in operating turbine engines. The impact velocity was varied to introduce a wide range of damage. Impact damage was quantified by nondestructive testing including x-radiography

and photography. A plot of the maximum fatigue stress versus number of cycles to failure (S-N curve) was generated for undamaged composite specimens to provide base line data. A fracture analysis of the impact damage and residual strength study was conducted with Ti-6-4 for comparison to the composite results.

The residual strength results are displayed in Figure 6. The behavior was very similar to that found for soft body impacts (Figure 2). Damage occurred at lower velocities than for soft body impacts. The residual strength at high impact velocities, where clean plugging occurred, was independent of impact velocity. The intermediate velocity region showed considerable strength degradation, especially at high prestress levels. Prestress increased the apparent impact damage and for prestresses above 300 MN/m^2 the samples broke with impact velocities near 150 m/s. The principal difference between the hard and soft body impacts was that the residual strength degradation began at much lower velocities for hard body impacts than for soft body impacts (∿ 500 m/s for soft bodies).

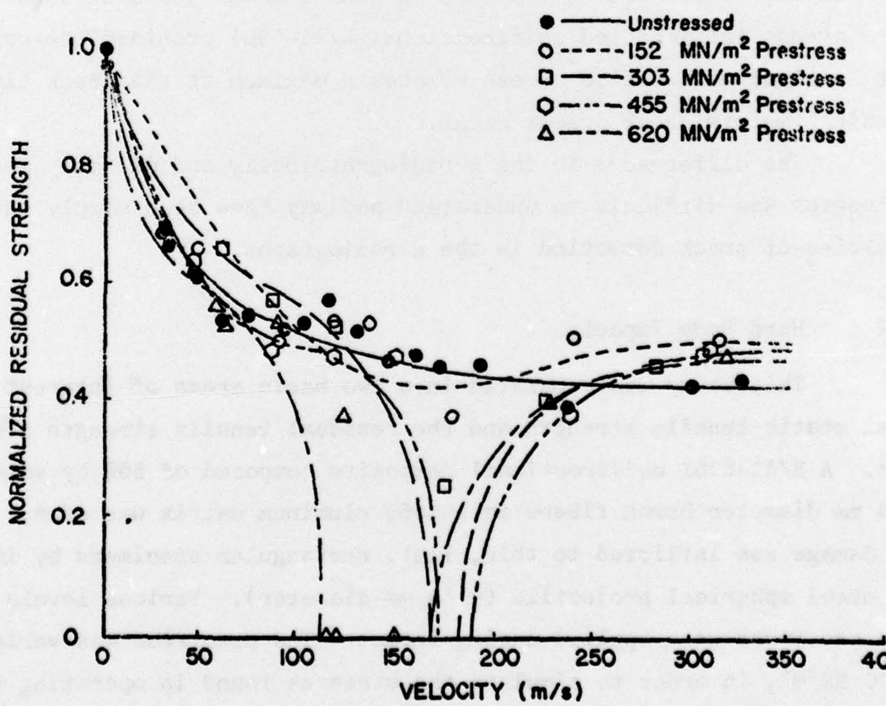

Figure 6. Normalized Residual Strength Versus Impact Velocity for B/Al-6061 Impacted with Steel Spheres. (From Carlisle[3]).

The velocity of maximum damage was lower for hard bodies than for soft bodies (150 m/s vs. 700 m/s). The normalized residual strength at high velocities was almost identical in both cases (∿ 0.5). The residual strength of Ti-6-4 was not measurably degraded for the velocities tested (up to 760 m/s).

Tensile fatigue tests were hampered by the same difficulties as reported in the preceeding section (propagation of longitudinal cracks, failure of doubler bonding and lack of repeatable fatigue failures). Therefore, the specimens were fatigued until longitudinal cracks propagated from the impact point to the doublers. The residual tensile strength was then measured. As for the soft body impacts, post impact fatigue *increased* the residual strength, the explanation being that fatigue blunts transverse cracks.

A fracture mechanics analysis of the tests was conducted and the results are shown in Figure 7. There was a marked resemblance to the soft body impact results (Figure 5) although the fracture toughness was slightly lower.

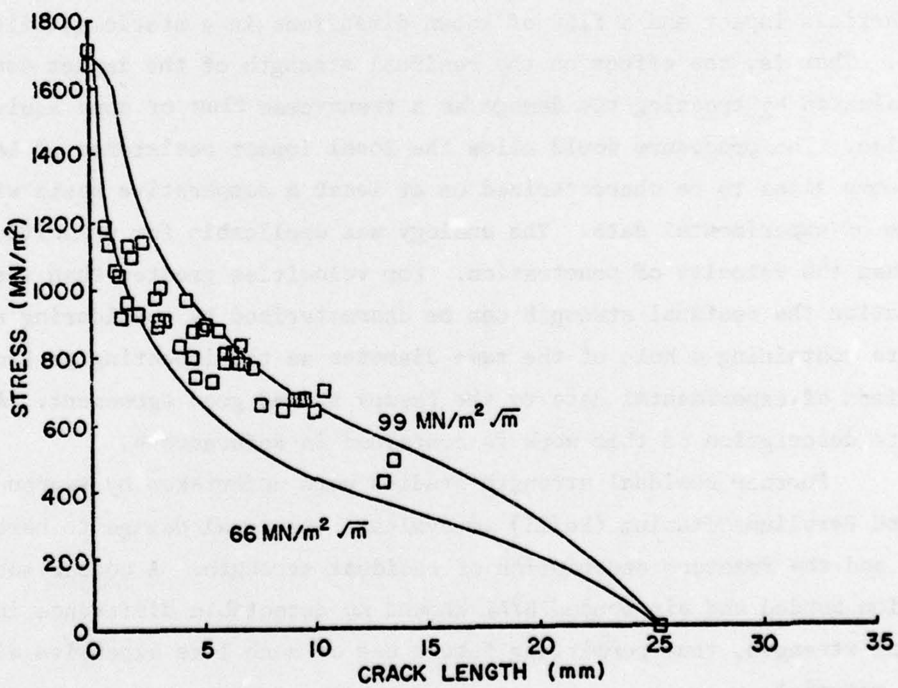

Figure 7. Crack Length Versus Residual Tensile Stress for B/Al-6061 at All Prestress Levels. (From Carlisle[3]).

This descrepancy may be due to material differences or to differences in the determination of crack length.

A complete description of the experiments and results was reported by Carlisle[3]. His main conclusions are summarized as follows.

For a given level of impact velocity B/Al-6061 suffered much greater degradation of ultimate tensile strength than did Ti-6-4. The addition of a tensile prestress during impact to B/Al-6061 severely reduced the residual tensile strength in a velocity range near the velocity of penetration. Tensile fatigue of B/Al-6061 produces longitudinal cracks which blunt the stress intensity effects of the transverse cracks produced by impact damage. The residual tensile strength after fatigue was greater than for the unfatigued damaged specimens. A fracture mechanics model fits the failure stress versus crack size data for B/Al-6061.

The hard body impact damage analysis reported by Carlisle[3] and Gray[1] was subsequently extended by Husman et. al.[4]. A more complete fracture analysis was conducted and an experimental program undertaken to verify the conclusions. A glass-epoxy composite was employed.

An analogy was developed between damage inflicted by a localized hard particle impact and a flaw of known dimensions in a static tensile coupon. That is, the effect on the residual strength of the impact damage was evaluated by treating the damage as a transverse flaw of some equivalent dimension. The procedure would allow the local impact resistance of laminated composites to be characterized on at least a comparative basis with a minimum of experimental data. The analogy was applicable for velocities less than the velocity of penetration. For velocities greater than that for penetration the residual strength can be characterized by considering a laminate containing a hole of the same diameter as the impacting particle. Comparison of experimental data to the theory showed good agreement. A complete description of this work is contained in Reference 4.

Further residual strength studies were undertaken by Awerbuch on B/Al and Berylium/Titanium (Be/Ti) to evaluate the local damage to hard body impact and the fracture description of residual strength. A comparison of diffusion bonded and air bonded B/Al showed no detectable difference in residual strength, thus permitting future use of much less expensive air bonded material.

Good agreement with the predicted residual strength was obtained

for B/Al, Borsic*/Ti and a resin matrix composite. In addition, the residual velocity of the impacting projectile was predicted using a simple analytic model and showed good experimental agreement. This work is continuing and will be reported in detail by Jonathan Awerbuch, an N. R. C. Research Associate at the AFML.

2.2 STRUCTURAL RESPONSE OF CANTILEVER BEAMS

Cantilever mounted specimens were used extensively in the materials response investigation described above. The loading of the material and certain impact failure modes (e.g., root failure) are functions of the structural response of the specimen. An investigation of the structural response and structural failure modes of cantilever mounted specimens was therefore undertaken.

Specimens 1.0 cm wide were mounted as cantilever beams with a 10.2 cm free end. They were impacted on axis 8.2 cm from the mount. The projectiles were 7.50 mm by 7.50 mm right circular cylinders made from RTV-11 (a silica rubber). The impact and subsequent beam response were observed with a framing camera, a streak camera and strain gages. Natural frequencies, velocities and deflections were measured.

The beam was modelled with a simple lumped parameter description. The structure was treated as a mass-spring system (or systems if more than one mode of response was considered) and the response was calculated by solution of the equations describing the system. The experiments, analytic model and results are described in detail by Tsai, et. al.[5]. A comparison of predicted and measured deflections is shown in Figure 8. Resonant frequencies were calculated and the calculated results show good agreement with the measurements for a variety of materials.

2.3 IMPACT STRENGTH OF CERAMICS

A short program was initiated to investigate the impact strength of ceramics typical of those that might be employed in the high temperature turbine stages of a jet engine. The materials investigated were:

1. Coors Al_2O_3, AD-998
2. Norton Si_3N_4, NC-132
3. Norton SiC, NC-203

* Registered trademark.

4. Norton SiC, NC-435

5. Sialon, 50 M/O Si_3N_4 - 25 M/O Al_2O_3 - 25 M/O AlN

Samples of the material were impacted with steel balls 12.7 to 15.9 mm in diameter in a drop weight test. The material was tested at room temperature and at 1300°C. The low velocities required for testing were obtained by dropping the balls from a controlled height. Higher velocity impacts were obtained using a powder gun range. Both instrumented (strain gaged samples) and uninstrumented tests were conducted. The drop weight test results were thoroughly investigated and reported by Bronski.[6]

He found that there are two modes of impact failure in ceramics; the initiation of crack growth from existing flaws by bending stresses in the material and the initiation of crack growth from localized Hertgrain cracks in impact area. The drop weight tests did not generate Hertgrain cracks, so the failures were all due to the propagation of cracks from existing flaws. Such cracks will propagate when the tensile component of the bending stress reaches a critical value. As ceramics display very little ductility, the elastic energy stored by the material at failure or the "impact fracture energy" is a good measure of the impact resistance of the material. The impact fracture energy is directly related to the dynamic strength of the material. The impact fracture energy was measured using the drop weight tests and the materials were ranked according to "impact fracture energy". It was found that Si_3N_4, annealed, had the greatest impact resistance and required approximately 2.5 times as much energy to fracture as the next best material. It was concluded that, as the impact fracture energy is related to the dynamic strength of the material, advances in ceramic impact strength require increases in the dynamic strength of the material. The results and conclusions are reported in greater detail by Bronski.[6]

SECTION III

DISCUSSION AND CONCLUSIONS

In the local damage tests conducted on B/Al-6061 and Ti-6-4 the B/Al-6061 displayed much lower performance than Ti-6-4. Impact damage threshold velocities were many times lower in B/Al-6061 than in Ti-6-4. At a given impact velocity B/Al-6-61 displayed greater sensitivity to damage and reduced residual tensile and fatigue strength, as compared to Ti-6-4. It must be concluded that either B/Al-6061 is an inferior material from an FOD resistance point of view, or that the tests were not realistic assessment of FOD tolerance. The B/Al-6061 certainly displays greater damage sensitivity at the impact conditions employed. However, these conditions were not typical of FOD events. The projectiles were smaller and the velocities were higher in tests than would normally be encountered in a real FOD event. Further work is required to extend these investigations to more realistic impact conditions (larger projectiles, lower velocities and edge impacts) and establish direct correlation between the subscale and fullscale material response.

The tests reported were conducted early in the B/Al development program and there have been significant advances in the fabrication of the material. More advanced B/Al-6061 may well display less impact sensitivity than the material investigated for this report. In addition, other combinations, such as B/Al-1100, could be more impact resistant and should be investigated.

The investigations of impact loaded cantilever beams demonstrated that a modal description of a cantilever beam can be used to describe structural response. The very simple lumped-mass description of the beam accurately predicted maximum deflections and natural frequencies. The impact load was adequately treated as an impulse for the conditions tested. The analysis should be extended to beams that are more characteristic of fan blades, that is, beams which have natural periods comparable to the impact loading time and higher vibrational modes are excited by the impact. In addition, edge impacts and the resultant torsional modes should be treated.

The investigation of the impact resistance of selected ceramics showed that the impact resistance is related to the dynamic strength and impact fracture energy of the material. A drop weight test was devised to measure the impact fracture energy and several advanced ceramics were ranked according

to impact fracture energy. Si_3N_4, annealed, proved to be the most impact resistant material tested. It was shown that increases in impact resistance will require increased material dynamic strength.

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